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CARBON STORAGE AFTER LONG-TERM GRASS ESTABLISHMENT ON DEGRADED SOILS

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Recent concern about global warming has led to attempts to estimate the effects of management on carbon sequestration in soil. The objective of this study is to determine the amount of soil organic carbon (SOC) degraded by agricultural practices and the rate of carbon sequestration in soils after restoration of grass for various periods of time. The SOC contents of previously cultivated clay soils (Udic Haplusterts) in central Texas returned to grass 6, 26, and 60 years ago are compared with those of soils in continuous agriculture for more than 100 years and those of prairie soils that have never been tilled. Surface (0 to 5 cm) SOC concentration ranged from 4.44 to 5.95% in the prairie to 1.53 to 1.88% in the agricultural sites. Carbon concentration in restored grasslands was generally intermediate to that reported for the native prairie and agricultural sites. The SOC mass in the surface 120 cm of the agricultural soils was 25 to 43% less than that of native prairie sites. After the establishment of grasses, SOC mass in the grass sites was greater than at the agricultural sites. A linear relationship between the length of time in grass and the amount of SOC sequestered in the surface 60 cm fit well for time periods from 6 to 60 years. The slope of this function provided an estimate of the carbon sequestration rate, in this case 447 kg C ha^{-1} yr^{-1}. At this rate, it would require nearly an additional century (98 years) for the 60-year grass site to reach a carbon pool equivalent to that of the prairie. (Soil Science 1999;164:718–725)

Key words: Soil Organic Carbon, prairie, grassland, agricultural soils.

INCREASING attention is being given to the accumulation of carbon dioxide, a potential 'greenhouse gas,' in the earth's atmosphere, and to the potential for global warming caused by the consequent 'greenhouse effect.' Carbon dioxide is increasing in the atmosphere, partly from the combustion of fossil fuels and also from changes in land use from forest and range ecosystems to agriculture (Mann 1986). Recent concerns about global warming have led to attempts to determine the total worldwide carbon stocks available (Batjes 1996).

Soils contain a vast reservoir of organic carbon and, with the selection of appropriate management strategies, may be used to store carbon that would otherwise be released to the atmosphere. Tillage effects on soil organic carbon (SOC) contents have been studied for a substantial period of time (Salter and Green 1933; Whiteside and Smith 1941). An estimated 5000 million metric tons of carbon have been lost from United States soils as a result of cultivation (Lal et al. 1999). In a review of soil management studies, Mann (1986) showed that SOC decreases rapidly with initial tillage, but then the rate of decrease declines in a nonlinear manner and gradually approaches a new, lower equilibrium. More recently, studies have been directed toward the potential increase in SOC with improved management practices, such as no-till, and the interaction of management with climate (Potter et al. 1998; Powlson et al. 1998).

Another management practice with the potential to increase soil carbon is returning agricultural soils to grassland or forest management

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practices (Bruce et al. 1999). Eighty-one years after conversion of long-term arable land to forest, more than twice as much SOC was present in the surface 23 cm than at the time of conversion (Jenkinson 1988). Little difference was found in C content or in C:N ratios in the surface 23 cm of soils under continuous grass for 120 years either receiving applications of inorganic N or with no fertilizer applied at Rothamstad, UK (Jenkinson 1988). In north-central Saskatchewan, soil carbon content increased 8 Mg C ha^{-1} in 11 years in the surface 0- to 37.5-cm depth on a hayed native grassland with annual applications of 112 kg N ha^{-1} and 11.2 kg S ha^{-1} (Nyborg et al. 1998). This suggests that the S fertilization may have resulted in C accumulation greater than or equal to the N fertilization.

Restoring native vegetation has recently been encouraged in the United States under government programs such as the Conservation Reserve Program (CRP). In Wyoming, carbon increased 5 years after reestablishing native grasses on clay loam soils previously tilled for 60 years, but only in the surface 2.5 cm with N-fertilization (Reeder et al. 1998). No increase in C content was found without fertilizer. In contrast, on a sandy loam soil, 5 years after reestablishing native grass on soils previously tilled for 60 years, soil carbon levels increased to that occurring in the A horizon of native range conditions. CRP land sequestered SOC at a rate of 1.1 tons C ha^{-1} yr^{-1} for the initial 5 years after returning agricultural land to grass in Kansas, Nebraska, and west Texas (Gebhart et al. 1994).

It is expected that the soil carbon will eventually approach a new equilibrium after reestablishment of grass vegetation that is similar to that of native grasslands. Nearly 200 years were required for soil organic N to reach equilibrium under grass planted on an old arable soil at Rothamsted (Jenkinson 1988). However, half of the increase in organic N was obtained in only 25 years. The time required for organic C to obtain equilibrium, especially under other climatic conditions, is uncertain as there is little long-term information concerning carbon sequestration.

The objective of our study is to determine the amount of soil organic carbon and the rate of carbon sequestration in soils previously degraded by agricultural practices after restoration of grass for various periods of time. The SOC content of soils returned to grass for 6, 26, and 60 years will be compared with that of soils in continuous agriculture for more than 100 years and with that of pristine prairie soils that have never been tilled.

MATERIALS AND METHODS

Site Description

Three areas in central Texas were identified as having sites with a unique combination of management histories: a pristine never-tilled native prairie site, an agricultural site that has a long history of inversion tillage, and a previously tilled site that had been returned to grass. Soils at all of the sites are Vertisols, with large montmorillonitic clay content in the soil profile.

Two areas are near Temple, Texas, one site with a 6-year-old restored grassland (designated the Temple area) and one site with a 26-year-old restored grassland (designated the Burleson area). The third area, with a 60-year-old restored grassland, is located near Riesel, Texas (designated the Riesel area). The three locations are within 75 kilometers of each other. Mean annual temperature for all locations was 19.5 °C. Average rainfall was 878 mm yr^{-1} for the Temple and Burleson locations and 908 mm yr^{-1} for the Riesel locations.

Soils at the Temple sites were classified as Houston Black clay (Udic Haplusterts). The 6-year restored grassland was sown to switchgrass (*Panicum virgatum* L.) in 1992. The Temple native prairie was predominately indiangrass (*Sorghastum nutans* (L.) Nash), little bluestem (*Schizachyrium scoparium* (Michaux) Nash), and Johnsongrass (*Sorghum halepense* (L.) Pers.), with some giant ragweed (*Ambrosia trifida* L.) present. The agricultural site had undergone spring tillage and had been planted to corn at the time of sampling in April 1998.

The soils at the Burleson sites were classified as Houston Black clay at the native prairie and as Branyon clay (Udic Haplusterts) at the grass and agricultural sites. The 26-year restored grassland vegetation was predominately indiangrass, little bluestem, switchgrass, big bluestem (*Andropogon gerardii vitman* var. gerardii), and sideoats grama (*Bouteloua curtipendula* (Michaux) Torrey). The native prairie vegetation was predominately little bluestem and indiangrass. The less diverse nature of the native prairie vegetation indicates that the site may have been overgrazed at some time in the past. The agricultural site had undergone spring tillage and had been planted to corn at the time of sampling in April 1998.

The soils at the Riesel sites were classified as Houston Black clay soils. The 60-year restored grassland vegetation was predominately King Ranch bluestem (*Bothriochloa ischaemum* var. songarica), little bluestem, indiangrass, and switchgrass. The native prairie vegetation was predominately King Ranch bluestem and little bluestem, with a strong influence of giant ragweed. The agricultural site had been tilled the previous fall and planted to winter wheat (*Triticum aestivum* L.) that had been grazed prior to sampling in April 1998.

Methods

Seven cores, 4 cm in diameter, were obtained from each site/surface condition using a plastic-lined hydraulic sampler that limited soil compaction. If compaction was observed, the core was discarded and another core taken. Soils were sampled to a depth of 120 cm. Cores were segmented to obtain depth increments of 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–60, 60–80, 80–100, and 100–120 cm. Soil segment wet weight was determined. The soil core was then split lengthways. Half the soil core segment was weighed, oven dried at 105 °C for 48 h, and the dry weight recorded. The soil water content was determined and used to correct the segment weight for calculating soil bulk density. The other half of the soil core was air dried until it crumbled easily, and easily identified organic matter such as roots, stems, leaves, and plant crowns was removed. The remaining soil was crushed to pass through a 2-mm sieve. A subsample of the cleaned sample was ground in a rolling grinder (Kelley 1994) in preparation for carbon analysis. The ground sample was oven dried for 3 h at 65 °C before burning.

Soil organic carbon was determined using a CR12 Carbon Determinator on samples weighing about 1 g (Chichester and Chaison 1991). Soil samples were burned at 575 °C, and CO_2 concentration in the airflow was determined with a solid state infrared detector. The combustion temperature was such that organic carbon was oxidized but inorganic carbon (i.e. CO_3) was not (Chichester and Chaison 1991; Rabenhorst 1988; Merry and Spouncer 1988). The CO_2 concentration was integrated over the duration of the burn to determine the sample C concentration. Soil samples were analyzed for total nitrogen on a FISON NA 1500 Nitrogen and Carbon Determinator (Fison Instruments, Dearborn, MI). Total mass of SOC and nitrogen were determined by multiplying the concentration times the soil bulk density.

Statistical Analysis

Data were analyzed using paired *t* tests to determine statistical significance at the (P = 0.05) level. An analysis of slope method was used to determine differences between regression analyses.

RESULTS

Bulk Density

Soil bulk density is an important factor in converting concentration values to mass values. Soil bulk density was generally lowest near the surface in the native prairie sites (Table 1). Soil bulk density was similar in the agricultural sites and restored grass sites, with the exception of the Riesel site. The Riesel agricultural site had been fall tilled, sown to small grain, and grazed. Soil consolidation from weathering and trampling by grazing animals resulted in a greater bulk density in the surface 15 cm in the agricultural site than in the restored grass site. The native prairie sites had lower bulk density values in the surface 60 cm than the agricultural and grass sites. Below 60 cm, bulk density was

TABLE 1

Mean soil bulk desity values for sampled sites

Depth —cm—	Grass	Agricultural	Prairie
		Mg m^{-3}	
Temple			
0–5	1.14±0.06†	1.13±0.18	0.74±0.15
5–10	1.28±0.02	1.13±0.07	1.04±0.06
10–15	1.34±0.05	1.25±0.03	1.18±0.03
15–20	1.38±0.02	1.30±0.03	1.21±0.03
20–30	1.41±0.03	1.32±0.02	1.31±0.02
30–40	1.42±0.05	1.32±0.04	1.35±0.04
40–60	1.44±0.07	1.33±0.04	1.42±0.04
60–80	1.46+0.07	1.38+0.03	1.47+0.04
80–100	1.50+0.08	1.45+0.04	1.50+0.03
100–120	1.53+0.08	1.41+0.09	1.49+0.05
Burleson			
0–5	0.97±0.11	1.04±0.08	0.89±0.11
5–10	1.18±0.05	1.08±0.17	1.02±0.06
10–15	1.28±0.04	1.34±0.10	1.15±0.03
15–20	1.30±0.06	1.41±0.03	1.26±0.03
20–30	1.36±0.02	1.41±0.03	1.35±0.03
30–40	1.40±0.01	1.44±0.03	1.40±0.07
40–60	1.46±0.03	1.50±0.06	1.49±0.04
60–80	1.52±0.03	1.57±0.04	1.57±0.05
80–100	1.59±0.03	1.65±0.03	1.61±0.03
100–120	1.67±0.02	1.74±0.03	1.63±0.12
Riesel			
0–5	1.07±0.09	1.40±0.16	1.01±0.07
5–10	1.30±0.10	1.43±0.11	1.06±0.09
10–15	1.35±0.11	1.48±0.10	1.13±0.10
15–20	1.41±0.12	1.45±0.06	1.20±0.09
20–30	1.46±0.08	1.44±0.07	1.29±0.09
30–40	1.50±0.04	1.48±0.06	1.39±0.04
40–60	1.52±0.01	1.52±0.06	1.48±0.05
60–80	1.57±0.03	1.61±0.11	1.53±0.05
80–100	1.67±0.09	1.69±0.11	1.59±0.05
100–120	1.74±0.08	1.83±0.13	1.71±0.13

†Mean ± standard deviation, n=7.

relatively uniform among all three surface conditions.

Soil Organic Carbon Concentration

Soil organic carbon concentration profiles for the three locations and surface conditions are presented in Table 2. Differences in SOC concentration between surface conditions were generally limited to the surface 60 cm. The native prairie sites had the greatest SOC concentrations, ranging from 4.44 to 5.95% in the surface 5 cm. The current agricultural sites had the lowest SOC concentrations, with values ranging from 1.53 to 1.88% in the surface 5 cm. The surface SOC concentrations found at the agricultural sites are typical of those reported for Houston Black soil (Potter and Chichester 1993). SOC concentration was uniform in the surface 10 cm, reflecting the mixing caused by tillage. SOC declined with depth in all cases, but it was generally lower at the agricultural and restored grass sites than at the native prairie sites at the deeper depths. Carbon concentrations in grass sites were intermediate to those reported for the prairie and agricultural sites.

Carbon Mass

Intensive agricultural practices and the resulting erosion and organic carbon oxidation have resulted in large losses in SOC in the agricultural soils compared with the pristine native prairie sites (Fig. 1). The organic carbon mass in the surface 120 cm of the agricultural soils was 25% lower at the Temple site, 43% lower at the Riesel site, and 33% lower at the Burleson site compared with the native prairie sites. Results were similar for the surface 60 cm, with the exception of the Temple agricultural site, which contained 30% less organic carbon than the Temple native prairie. Losses of SOC with tillage occur in relatively short periods of time, after which soils approach a new equilibrium state (Mann 1986). The agricultural sites in this study had been in cultivation for about 120 years, and SOC had obtained a nearly steady state with the use of tillage. The grass sites had been in cultivation for a minimum of 60 years before grass was established.

With the establishment of grasses and lack of tillage, organic carbon contents in the grass sites were numerically larger than in the agricultural sites, although only significantly greater at the 60-year grass site at Riesel (Fig. 1). Trends were most apparent in the surface 60 cm, with SOC mass increasing with longer length of time in grass. The organic carbon mass in the restored grassland was always intermediate between the agricultural site and the native prairie site for the surface 120 cm and the surface 60 cm.

Total Soil Nitrogen Concentration

Nitrogen concentration values, although much lower, followed trends similar to the SOC values (Table 3). Nitrogen concentration was greater near the surface than at depth. The agricultural sites had lower nitrogen concentrations than the grass sites, which had lower concentrations than the prairie sites. Nitrogen concentration values increased with increasing length of time in grass in the surface 40 cm. Below 40 cm, N concentrations were closer to those of the agricultural sites than those of the prairie sites.

TABLE 2
Mean soil organic carbon concentration values

Depth	Grass	Agricultural	Prairie
—cm—		—— % ——	
Temple			
0–5	2.22±0.15†	1.80±0.11	5.95±1.84
5–10	1.73±0.15	1.72±0.10	3.08±0.25
10–15	1.57±0.16	1.72±0.08	2.56±0.17
15–20	1.43±0.24	1.56±0.11	2.28±0.15
20–30	1.30±0.33	1.38±0.12	1.87±0.13
30–40	1.20±0.39	1.27±0.16	1.69±0.18
40–60	1.06±0.37	1.13±0.23	1.35±0.15
60–80	1.06±0.37	0.96±0.13	1.11±0.20
80–100	0.87±0.35	0.84±0.14	1.02±0.26
100–120	0.65±0.25	0.73±0.13	0.90±0.39
Burleson			
0–5	2.45±0.38	1.53±0.10	4.44±0.41
5–10	1.73±0.16	1.54±0.16	3.14±0.12
10–15	1.52±0.13	1.25±0.11	2.74±0.22
15–20	1.48±0.10	1.25±0.08	2.36±0.22
20–30	1.31±0.19	1.23±0.16	1.93±0.19
30–40	1.15±0.13	1.14±0.20	1.53±0.22
40–60	0.95±0.10	0.92±0.15	1.11±0.24
60–80	0.70±0.10	0.67±0.14	0.80±0.23
80–100	0.50±0.04	0.46±0.11	0.64±0.17
100–120	0.35±0.13	0.25±0.09	0.47±0.13
Riesel			
0–5	3.86±0.31	1.88±0.19	5.49±0.70
5–10	2.45±0.14	1.85±0.18	3.65±0.44
10–15	2.17±0.05	1.58±0.15	3.26±0.48
15–20	1.97±0.13	1.51±0.10	2.83±0.41
20–30	1.64±0.26	1.29±0.30	2.27±0.42
30–40	1.36±0.13	0.96±0.37	1.96±0.37
40–60	0.76±0.20	0.80±0.45	1.48±0.40
60–80	0.42±0.10	0.56±0.50	1.06±0.25
80–100	0.29±0.10	0.39±0.45	0.85±0.25
100–120	0.18±0.09	0.22±0.25	0.64±0.05

†Mean ± standard deviation, n=7.

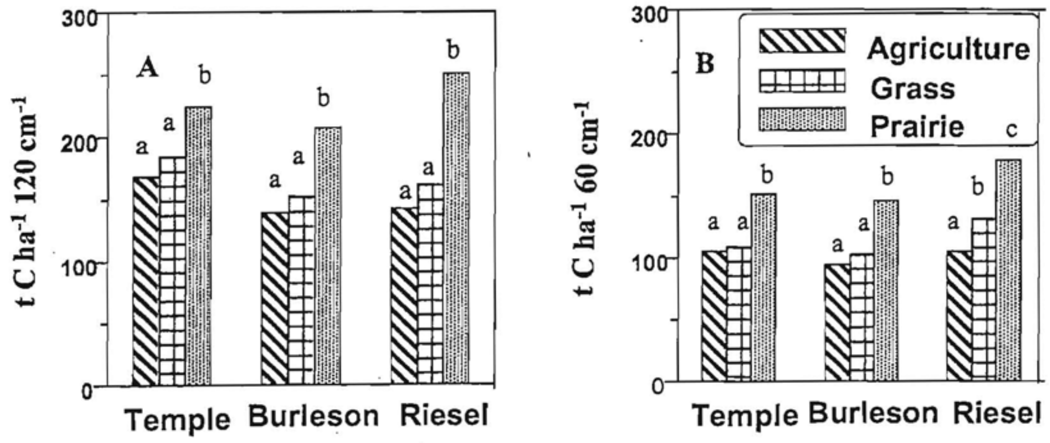

Fig. 1. Soil organic carbon in the surface 120 cm (A) and 60 cm (B) of prairie, restored grassland, and agricultural soils.

Nitrogen Mass

Total N mass in the surface 120 cm was similar in the agricultural and grass sites and significantly larger in the prairie sites (Fig. 2). Total N values in the surface 120 cm of the agricultural sites were 73%, 68%, and 71% of those in the prairie sites for the Temple, Burleson, and Riesel areas, respectively. In the surface 60 cm, total N values in the agricultural sites were 67%, 63%, and 70% of those in the prairie sites for the Temple, Burleson, and Riesel sites, respectively. N mass in the grass sites was similar to that in the agricultural sites for periods of 6 and 26 years. After 60 years in grass, the N mass in the surface 60 cm was significantly greater than that in the agricultural site but still significantly less than that occurring in the prairie site.

Total soil N was highly correlated with SOC when calculated on a mass per unit volume basis (Fig. 3). This held true for samples taken from depth increments near the surface (0 to 5 cm) to depths of 90 to 120 cm. Linear relationships were developed using regression analysis to relate total N mass to SOC mass. Slopes of these relationships varied from 11.2 to 16.4 for the agricultural sites, 14.1 to 16.5 for the grass sites, and 11.4 to 13.4 for the prairie sites. Analysis using a linear model to compare slopes showed that slopes among the agricultural, grass, and prairie sites were not significantly different, with the exception that the agricultural site slope was significantly lower than that of the 60-year grass and prairie sites at Riesel. The reason for the lower slope on the Riesel agricultural site is not known at this time but may have been caused by erosion.

TABLE 3

Mean soil total nitrogen concentration values

Depth	Grass	Agricultural	Prairie
—cm—		%	
Temple			
0–5	0.15±0.018†	0.14±0.005	0.44±0.071
5–10	0.12±0.006	0.13±0.007	0.24±0.032
10–15	0.11±0.006	0.12±0.007	0.19±0.043
15–20	0.10±0.013	0.10±0.004	0.18±0.024
20–30	0.09±0.021	0.09±0.006	0.13±0.008
30–40	0.08±0.025	0.09±0.008	0.12±0.022
40–60	0.07±0.022	0.07±0.007	0.09±0.006
60–80	0.07±0.016	0.06±0.006	0.07±0.011
80–100	0.06±0.016	0.06±0.006	0.06±0.008
100–120	0.05±0.011	0.05±0.006	0.06±0.025
Burleson			
0–5	0.18±0.021	0.13±0.010	0.35±0.031
5–10	0.13±0.004	0.13±0.009	0.27±0.013
10–15	0.11±0.005	0.10±0.008	0.23±0.012
15–20	0.11±0.007	0.10±0.004	0.20±0.013
20–30	0.10±0.004	0.10±0.006	0.16±0.012
30–40	0.09±0.005	0.09±0.008	0.13±0.017
40–60	0.08±0.007	0.08±0.010	0.10±0.014
60–80	0.06±0.006	0.06±0.008	0.08±0.014
80–100	0.05±0.002	0.05±0.006	0.06±0.009
100–120	0.04±0.005	0.04±0.004	0.05±0.006
Riesel			
0–5	0.29±0.030	0.17±0.010	0.39±0.039
5–10	0.19±0.016	0.15±0.027	0.28±0.036
10–15	0.16±0.009	0.11±0.045	0.24±0.034
15–20	0.14±0.018	0.11±0.020	0.21±0.032
20–30	0.13±0.016	0.10±0.026	0.19±0.040
30–40	0.11±0.008	0.09±0.019	0.15±0.036
40–60	0.08±0.012	0.08±0.019	0.10±0.033
60–80	0.06±0.005	0.06±0.022	0.09±0.029
80–100	0.04±0.016	0.05±0.021	0.09±0.032
100–120	0.02±0.010	0.03±0.014	0.05±0.005

†Mean ± standard deviation, n=7.

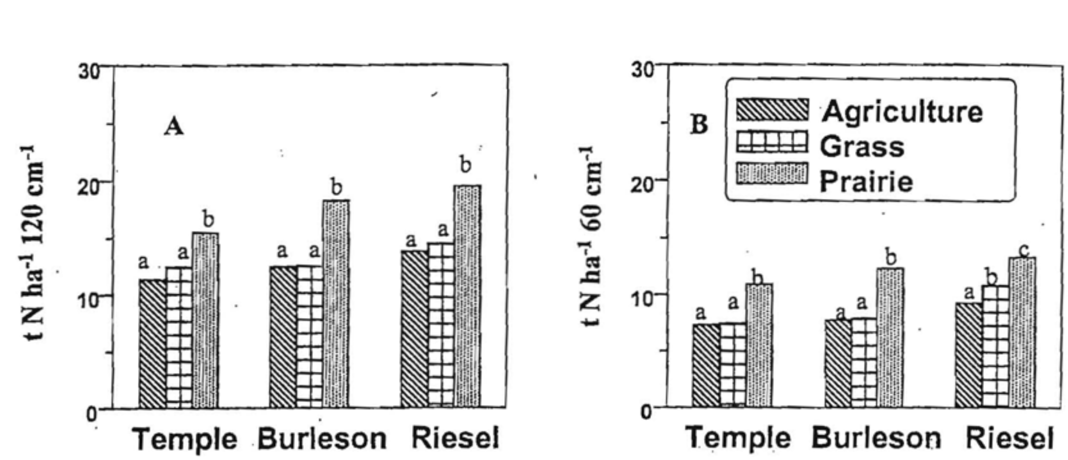

Fig. 2. Total nitrogen in the surface 120 cm (A) and 60 cm (B) of prairie, restored grassland, and agricultural soils.

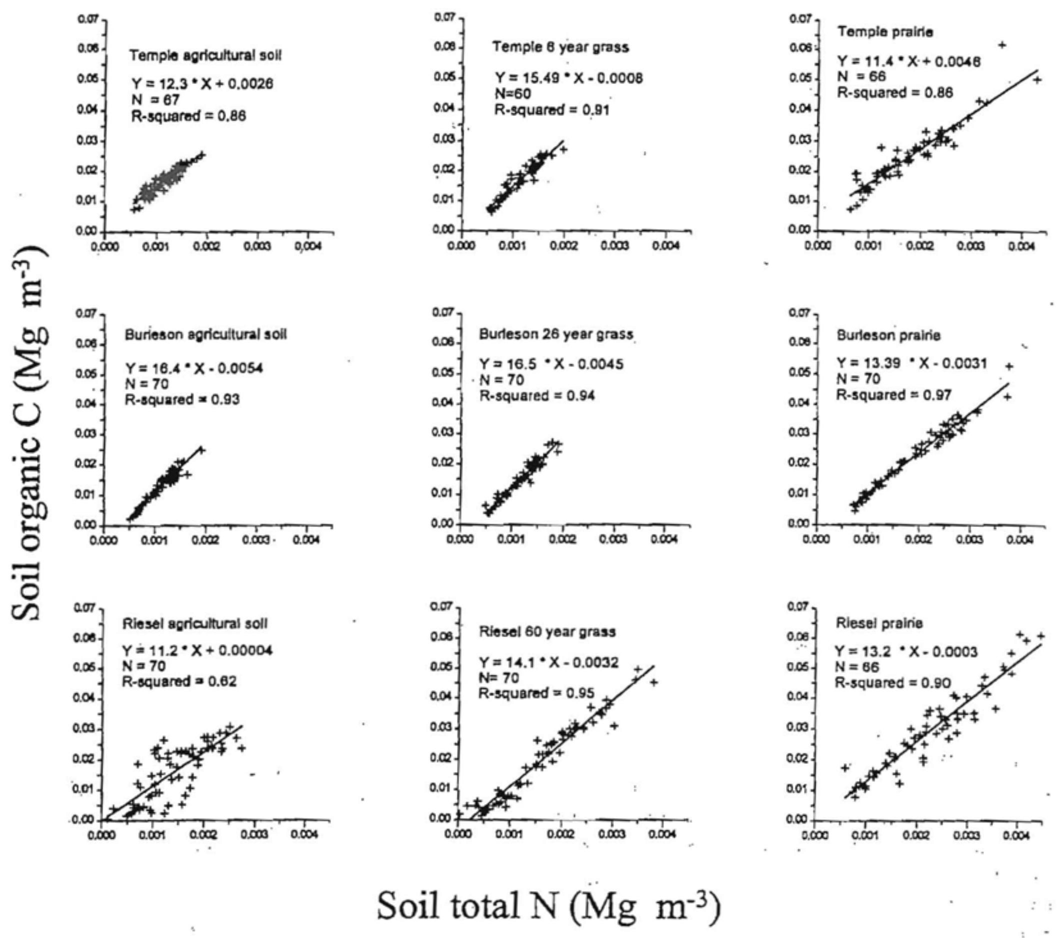

Fig. 3. Relationships between soil organic carbon and total nitrogen in the surface 60 cm for three sites and three surface conditions.

The data variability was greater at the agricultural site, with an r^2 value of 0.62 compared with r^2 values of 0.95 and 0.90 at the Riesel 60-year grass site and prairie, respectively.

DISCUSSION

The amount of carbon sequestered from grass establishment was estimated by calculating the difference in mean SOC mass between the grass site and the associated agricultural site for the surface 60 cm. Using regression analysis, a relationship was established between the length of time in grass and the amount of SOC sequestered (Fig. 4). A linear function fit the data well for time periods from 6 to 60 years. The slope of this function provided an estimate of the rate of carbon sequestration, in this case 447 kg C ha^{-1} yr^{-1}. This estimate is lower than the carbon sequestration rate of 1100 kg C ha^{-1} yr^{-1} reported after the first 5 years of grass on CRP areas in the Great Plains (Gebhart et al. 1994). This may be caused by differences in climate, soils, or grass species. Grasses vary in root/shoot ratios, the distribution of roots within the soil profile, and the rate and amount of C transferred from the plant to the soil via root turnover rates and amounts of root exudates (Frank, et al. 1995). The carbon sequestration rate for grass determined in this study is 1½ times the carbon sequestration rate reported for the first 10 years after conversion to no-tillage management practices with a corn (*Zea mays* L.) -wheat—grain sorghum (*Sorghum bicolor* L.) rotation on Houston Black soils (Potter et al. 1998).

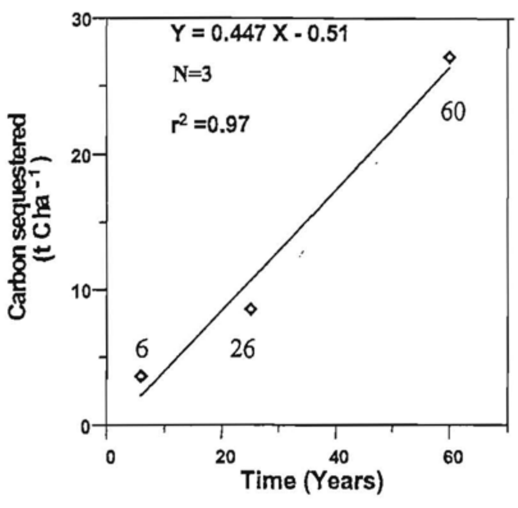

Fig. 4. Carbon sequestered in the surface 60 cm after various periods of grass establishment on previously tilled sites.

A question of great concern is how long soils can serve as a sink for carbon. Estimates vary upward from as little as 25 years (Lal et al. 1998). We did not find an apparent decline in SOC sequestration with time in this study. If the native prairie is used as an estimate of the potential amount of carbon sequestration possible in soils under current climatic conditions, then the SOC present in the surface 60 cm after 60 years of grass represents 70% of the total possible carbon sequestration. This means an additional 44 t C ha^{-1} could possibly be sequestered, although the time required for sequestration is unknown at this time. At the rate found in this study, it would require nearly an additional century (98 years) for the 60-year grass site to reach a carbon content equivalent to that of the prairie.

CONCLUSION

Soil organic carbon was reduced 30 to 43% by agricultural practices in the surface 60 cm of heavy clay soils in central Texas. Returning the previously tilled soils to grass resulted in an increase in SOC in the surface 60 cm at a mean rate of 447 kg C ha^{-1} yr^{-1} for periods ranging from 6 to 60 years. There was no apparent decline in the rate of carbon sequestration for the time periods used in this study.

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REFERENCES

Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47:151–163.

Bruce, J. P, M. Fromme, E. Haites, H. Janzen, R. Lal, and K. Paustian. 1999. Carbon sequestration in soils. J. Soil Water Conser. 54:382–389.

Chichester, F. W., and R. F. Chaison. 1991. Analysis of carbon in calcareous soils using a two temperature dry combustion infrared instrumental procedure. Soil Sci. 153:237–241.

Frank, A. B., D. L. Tanaka, L. Hofmann, and R. F. Follett. 1995. Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing. J. Range Manag. 48:470–474.

Gebhart, D. L., H. B. Johnson, H. S. Mayeux, and H. W. Polley. 1994. The CRP increases soil organic carbon. J. Soil Water Conser. 49:488–492.

Jenkinson, D. S. 1988. Soil organic matter and its dynamics. *In* Russell's Soil Conditions and Plant

Growth, 11th Ed. A. Wild (ed.). John Wiley & Sons, New York, pp. 564–607.

Kelley, K. R. 1994. Conveyor-belt apparatus for fine grinding of soil and plant materials. Soil Sci. Soc. Am. J. 58:144–146.

Lal, R., R. F. Follett, J. Kimble, and C. V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54:374–381.

Lal, R., J. M. Kimble, R. F. Follet, and C. V. Cole. 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Press, Chelsea, MI.

Mann, L. K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279–288.

Merry, R. H., and L. R. Spouncer. 1988. The measurement of carbon in soils using a microprocessor controlled resistance furnace. Commun. Soil Sci. Plant Anal. 19:707–720.

Nyborg, M., M. Molina-Ayala, E. D. Solberg, R. C. Izaurralde, S. S. Malhi, and H. H. Janzen. 1998. Carbon storage in grassland soils as related to N and S fertilizers. *In* Management of Carbon Sequestration in Soil. R. Lal et al. (eds.). Advances in Soil Science. CRC Press, Boca Raton, FL, pp. 421–432.

Potter, K. N. and F. W. Chichester. 1993. Physical and chemical properties of a vertisol with continuous, controlled-traffic, no-till management. Trans. ASAE 36:95–99.

Potter, K. N., H. A. Torbert, O. R. Jones, J. E. Matocha, J. E. Morrison, and P. W. Unger. 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Till. Res. 47(3–4): 309–321.

Powlson, D. S., P. Smith, K Coleman, J. U. Smith, M. J. Glendining, M. Körschens, U. Franko. 1998. A European network of long-term sites for studies on soil organic matter. Soil Till. Res. 47(3–4): 263–274.

Rabenhorst, M. C. 1988. Determination of organic and inorganic carbon in calcareous soils using dry combustion. Soil Sci. Soc. Am. J. 52:965–969.

Reeder, J. D., G. E. Schuman, and R. A. Bowman. 1998. Soil C and N changes on conservation reserve program lands in the Central Great Plains. Soil Till. Res. 47(3–4):339–349.

Salter, R. M., and T. C. Green. 1933. Factors affecting the accumulation and loss of nitrogen and organic carbon in cropped soils. J. Am. Soc. Agron. 25: 622–630.

Whiteside, E. P. and R. S. Smith. 1941. Soil changes associated with tillage and cropping in humid areas of the United States. J. Am. Soc. Agron. 33:765–777.